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Technology Demonstration of a Microwave-Assisted Lead-Based Paint Removal Process

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Construction Engineering Research Laboratory

Environmental Technology Demonstration

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Final Report

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ABSTRACT: The microwave-assisted paint removal process is a viable alternative to the currently used technologies for lead-based paint (LBP) removal, such as abrasive blasting and chemical stripping. Two design approaches for the microwave paint removal systems were evaluated for removal of LBP. Graphite-based susceptor materials, applied over the painted surface, were used successfully in absorbing the microwave energy and heating the paint. The heat softened the paint, which was easily scraped from the substrate. The microwave paint removal process was optimized in the laboratory and field demonstrated for a wooden window sill and trough at Fort Lewis, WA. The lead levels on the relatively flat substrates and complex shaped substrates were dramatically reduced on the areas stripped. Chemical stabilizers applied over the LBP prior to application of the susceptor rendered the waste nonhazardous by the current Resource Conservation and Recovery Act (RCRA) Toxicity Characteristic Leaching Procedure (TCLP) criteria. The microwave-assisted removal process is safe and effective in removing paint without burning, discoloring, or otherwise damaging the substrate.

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Conversion Factors

U.S. standard units of measure can be converted to SI* units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic inches	0.00001638706	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(5/9) x (°F – 32)	degrees Celsius
degrees Fahrenheit	(5/9) x (°F – 32) + 273.15.	kelvins
feet	0.3048	meters
gallons (U.S. liquid)	0.003785412	cubic meters
horsepower (550 ft-lb force per second)	745.6999	watts
inches	0.0254	meters
kips per square foot	47.88026	kilopascals
kips per square inch	6.894757	megapascals
miles (U.S. statute)	1.609347	kilometers
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square meters
square miles	2,589,998	square meters
tons (force)	8,896.443	newtons
tons (2,000 pounds, mass)	907.1847	kilograms
yards	0.9144	meters

* SI: *Système International d'Unités* (International System of Measurement).

Preface

This technology demonstration was conducted for Headquarters, Department of the Army under Program Element (PE) 063728A, "Environmental Technology Demonstration Project 002, "Environmental Compliance Technology"; Work Unit CF-M B101, "Cost Effective Technologies to Reduce, Characterize, Dispose, and Reuse Sources of Lead Hazards." Bryan Nix, ACS (IM)-FDF, was the Technical Monitor.

The work was performed by the Materials and Structure Branch (CF-M) of the Facilities Division (CF) Construction Engineering Research Laboratory (CERL). The CERL Principal Investigator was Dr. Ashok Kumar. A portion of this work was done by HVS Technologies, Inc, State College, PA, under Contract DACA42-01-P-0031. X-ray fluorescence measurements for the field test were carried out by Karen Hunter of Hart Crowser, Inc., Seattle, WA. The Technical Editor was Marsha C. Gay, Information Technology Laboratory – Vicksburg. Martin J. Savoie is Chief, CEERD-CF-M and L. Michael Golish is Chief, CF. The Technical Director of the Installation Operations business area is Gary W. Schanche (CV-ZT), and the Director of CERL is Dr. Alan W. Moore.

CERL is an element of the U. S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL James R. Rowan, EN, and the Director is Dr. James R. Houston.

Executive Summary

Lead-based paint (LBP) was widely used in many buildings prior to the ban on its use enacted by the EPA in 1978, based on the dangers of lead in LBP. The Department of Defense (DoD) used LBP on the interior and exterior of many wooden buildings constructed prior to 1978. It is estimated that there still 2 billion square feet of LBP covering wood surfaces in buildings owned by the DoD.

Current technologies for the removal of LBP from wooden substrates rely on: (1) abrasive blasting, (2) power tools, (3) chemical stripping, or (4) heat guns followed by scraping. However, these technologies have the disadvantages of introducing vapors from toxic chemicals and/or lead dust into the air, as well as creating leachable lead waste that must be disposed in a hazardous waste landfill.

The microwave-assisted paint removal process was developed for removal of LBP from wooden substrates. The use of graphite-based susceptors applied on top of the paint was optimized in laboratory experiments to efficiently heat and soften the paint. In addition, the use of chemical stabilizers, applied directly to the LBP, allowed the microwave-softened paint to be scraped off as a nonhazardous waste.

A field demonstration of microwave-assisted LBP removal along with the use of chemical stabilizers was conducted on a wooden window frame at Fort Lewis, Washington. It was demonstrated that the amount of lead dust released into the air, as well as the leachable lead in the paint scrapings as determined by Toxicity Characteristic Leaching Procedure (TCLP) were within the allowable limits. A production and cost analysis of the LBP removal process were also presented. The method demonstrated the following advantages: (1) it can be performed at a relatively low temperature, so that it does not have the potential to cause a fire; (2) it does not harm the wood surface; (3) it renders the removed LBP debris nonhazardous so that it can be disposed in a regular landfill.

A portable personal breathing zone airborne lead dust analyzer, called the Aerolead was evaluated during this demonstration against conventional air monitoring. The Aerolead was operated for periods of 30 minutes during the microwave-assisted lead removal process, the analysis was performed onsite within 7 minutes. The Aerolead readings indicated permissible exposure limits of 5.18 micrograms/m^3, which was consistent with the laboratory-analyzed personal air monitor filters analysis of less

than 35 micrograms/m^3. Both results are less than the permissible exposure limits of 50 micrograms/$m,^3$ 8-hour time-weighted average (TWA).

This demonstration met the performance requirements, which were to: (1) remove existing LBP, (2) comply with environmental standards, (3) comply with worker health and occupational safety requirements, (4) determine performance of the microwave assistant paint removal process, and (5) conduct cost and benefits assessment.

Currently, a variation of this technology is being employed by some companies in Sweden and Denmark. However, in the European application the windows are removed from their setting, placed into an industrial microwave oven, and heated to soften the paint, so that it is easily removed. Specially configured tools have been designed to scrape the paint efficiently. These companies have demonstrated that paint can be removed with or without the use of a susceptor, depending on the moisture content of the wooden substrate.

The cost of the microwave–assisted LBPremoval process is projected to be \$22.68 per sq ft, compared with \$34.68 per sq ft for chemical stripping, resulting in a cost saving of \$12 per sq ft, or 35 percent, compared with costs for the chemical stripping process. If the *in situ* LBP removal process can be further developed to achieve the higher heating efficiency of the industrial microwave ovens, with appropriate microwave shielding, additional cost savings could be realized. It is projected that for this case the time would be reduced by 2.1 hours. The total cost would be \$10.80 per sq ft. This represents a cost savings of \$23.88 (69 percent) over the chemical stripping process.

This technology appears to be particularly suitable to niche markets where preservation of the wood in historical building components is an important concern. The development prototype microwave device that can be clamped onto a window frame has been designed to remove LBP *in situ*, while maintaining microwave safety levels.

1 Introduction

Background

The Army owns an estimated 95,400 target facilities in the United States and 26,200 in foreign countries. The average age of these facilities is 36 years. Since 90,000 were built before 1978, they probably contain some lead based paint (LBP). Furthermore, about 2,600 of these facilities are on or eligible for the National Register of Historic Places, and require special procedures for preservation. Current removal methods for hazardous paint that contain lead all have some shortcomings. This includes chemical stripping, abrasive blasting, vacuum-assisted power tools, and high-intensity xenon lamps. Methylene chloride based chemical strippers are suspected carcinogens and the Occupational Safety and Health Administration (OSHA) has stringent requirements for worker protection. Methylene chloride is also classified as a Hazardous Air Pollutant (HAP) and is regulated by the U.S. Environmental Protection Agency (EPA). Alternative environmentally friendly chemical strippers are slow and create a large quantity of hazardous waste from the rinse water.

Abrasive blasting may require as much as 2.2 kg of abrasive per square foot. This large quantity of waste is usually hazardous because of the presence of lead in the paint chips. The cost of abrasive blasting is further increased by the containment structures generally required for environmental and worker protection. Abrasive blasting cannot be used inside the building because of the lead dust that is generated. Vacuum blasting is slow and carries the risk of lead dust escaping. Therefore, there is a need for an affordable, environmentally acceptable technology to remove deteriorating LBP from DoD facilities.

Objective

The objective of this research was to conduct a technology demonstration of microwave-assisted removal of LBP from wooden window sills and troughs using various chemical stabilizers that render the LBP nonhazardous upon removal. A microwave applicator was adapted for use on the window sills and troughs, and laboratory experiments were carried out on removal of paint from a window frame mock-up. A suitable window frame coated with LBP in an abandoned wooden building at Fort Lewis, Washington, was selected for field-demonstration of the actual process of microwave-assisted LBP removal.

Approach

Technology for microwave-assisted removal of LBP, including the use of susceptors and chemical stabilizers, was developed and optimized in laboratory experiments. The microwave applicator used in laboratory experiments was modified for the window sill and trough geometric configuration. The technology demonstration and assessment were conducted at an abandoned wooden building at Fort Lewis, Washington, in March 2001.

Mode of Technology Transfer

Technology transfer is being accomplished by: (1) a Technology Transfer Implementation Plan supervised by the U. S. Army Environmental Center (AEC); (2) dissemination of Public Works Technical Bulletin (PWTB) 420-70-2, "Installation Lead Hazard Management"; (3) participation in User Groups and Committees such as the Army Lead and Asbestos Hazard Management Team, Federal Lead-Based Paint Committee Meetings at EPA or HUD, and ASTM Committee E06.23 on Lead Hazards Associated with Buildings; (4) websites maintained by the Assistant Chief of Staff for Installation Management (ACSIM) [http://www.hqda.army.mil/acsimweb/fd/policy/facengcur.htm], AEC [http://aec. army. mil/usaec/], and the U. S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC/CERL) [http:// www.cecer.army.mil], as well as the Hands-on-Skills Training (HOST) website [http://www.hqda.army.mil/acsimweb/fd/policy/host/index.htm]; (5) demonstration and validation of emerging technologies through Army technology demonstration funding (6.3) starting in fiscal year 2000 (FY00) and continuing through FY03, and cost/performance reports from those demonstrations, including a decision tree for selection of optimal LBP hazard management and removal techniques for buildings.

2 Technology Description

Microwave-Assisted Paint Removal Process

The process for microwave-assisted removal of LBP from wood was developed and patented at the U.S. Army Construction Engineering Research Laboratory (CERL) by Ashok Kumar (U.S. Patent No. 5,268,548) and assigned to the U.S. Army (Kumar 1993). In the microwave-assisted paint removal process, microwave coupling compounds (susceptors) are applied as a waterborne slurry or as a polymer binder paste on top of the existing painted surface. Graphite-based susceptor materials can reach temperatures up to 1000° C in less than a minute when exposed to microwaves (125 watts/cm^2) (Kumar and Boy 1998; Booth et al. 1999). The microwave applicator, which uses standard 2.45-GHz magnetron tubes that are also used in household microwave ovens, is designed to focus microwave energy onto the susceptor where it is absorbed effectively. The paint is debonded from the substrate by the heat from the microwaves and is removed easily by scraping. A microwave shield is provided for worker protection. Safety switches are used with the microwave applicator to make the system safe for the workers, and no extra clothing or suits are required for the operators. Since the airborne lead levels should be below the EPA and OSHA threshold requirements, containment structures, environmental monitoring, and worker health monitoring are not needed in this process.

HVS Microwave Paint Stripper

A 1000 watt microwave-assisted paint stripping system was developed by HVS Technologies, Inc. (Hollinger et al. 1996). The power supply contains the microwave generation components and safety interlock circuitry. The amount of reflected power can be minimized by impedance matching.

The applicator (Figure 1) contains the microwave energy and directs it onto the painted surface. The HVS applicator is a stub-tuned device, with an aperture specially designed as a microwave window that couples the microwave energy from the waveguide to the painted surface. Surrounding the aperture are four safety switches, which will not allow microwave energy to be generated unless the applicator is pressed against a flat surface. On the top near the base of the applicator is an exhaust tube that must be connected to a vacuum system and a high-efficiency particulate air (HEPA) filter during operation.

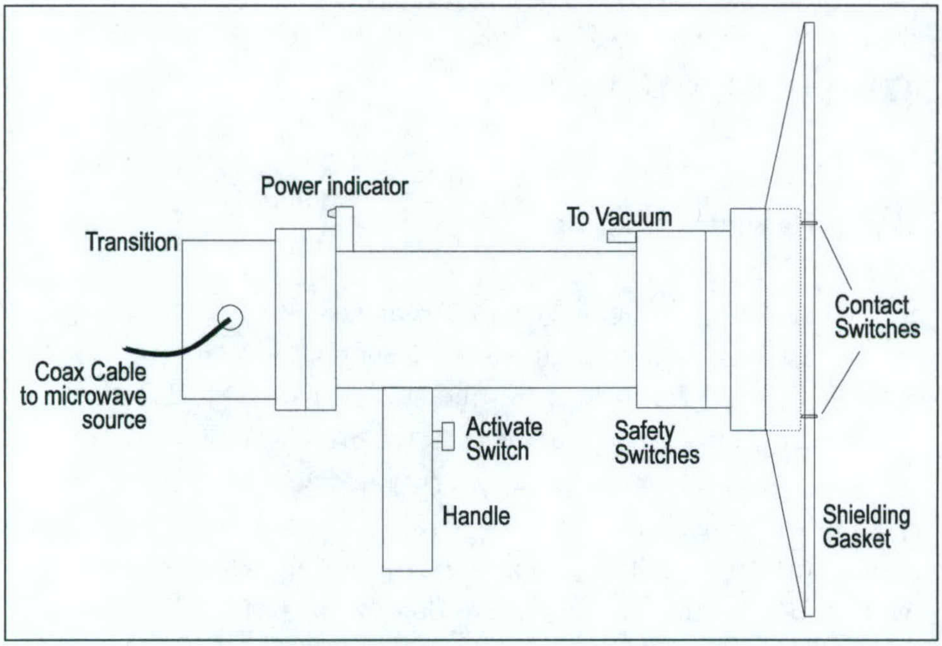


Figure 1. Microwave paint stripper applicator.

Susceptor and Stabilizer

A modified cementious material (PreTox 2000®) mixture was designed to be applied over LBP to chemically stabilize the lead. When LBP is coated with stabilizer and removed by the microwave heating and subsequent scraping, the resultant waste generated can be designated nonhazardous by current Resource Conservation and Recovery (RCRA) criteria and can be disposed of in regular landfills.

Laboratory testing has shown that the optimal combination of easy removal and nonhazardous waste product was achieved when PreTox 2000® was applied directly onto the LBP, allowed to dry, and coated with a mixture of a graphite-based slurry and graphite powder.

By heating the susceptor-stabilizer mixture with microwaves, it was determined that 464 cm^2 (72 sq in.) of LBP could be removed in about 5 minutes. This estimate includes heating times of approximately 3 minutes using the applicator, required to obtain a surface temperature of about 100 °C, and a scraping time of approximately 2 minutes.

Applicator Modification

To be able to use the applicator shown in Figure 1 on window sills and troughs, some modifications had to be carried out. Since the applicator was designed to work on flat surfaces, contact switches were incorporated to enable the microwave power to be generated only when the contact switches were active. This ensures that the shielding gasket is flush with the surface being stripped and hence prevents any leakage of microwaves, which could be hazardous to the operator. Since windowsills and troughs may contain grooves, there will be a gap between the applicator and the surface from which paint has to be stripped. This causes two problems with the existing applicator design. First, the contact switches will not be activated due to the gap and hence no microwaves will be generated. This problem was overcome by disabling the contact switches. The second problem, which is more important, is that this gap between the applicator and the window surface caused microwaves to leak from all around the shielding gasket. Using an accurate microwave leak detector, a leakage of about 8 to 10 mW/cm^2 was measured around the shielding gasket when the gap between the applicator and painted surface was about 2 in.

Although microwave field levels below 5 mW/cm^2 are considered safe by international standards, in the United States the safety limit is 8.2 mW/cm^2 at 2.45 GHz (Institute of Electrical and Electronics Engineers [IEEE] 1992).

This problem was solved by attaching a 2.5-in. wide and 1/32-in. thick shielding gasket skirt around the main shielding gasket using plastic ties. Slits 2 in. long and 1/8-in. apart were cut all around the skirt as shown in Figure 2. This enhanced the flexibility of the shielding skirt during the paint stripping operation. After the shielding skirt was attached, the microwave leakage was once again measured all around the skirt while maintaining a gap of about 2 in. between the applicator and the painted surface. The leakage was barely registered (1 mW/cm^2) on the leak detector. The slits also help prevent leakage from grooves as the gasket strips on the skirt fall into the grooves, cutting off a leakage path for the microwaves.

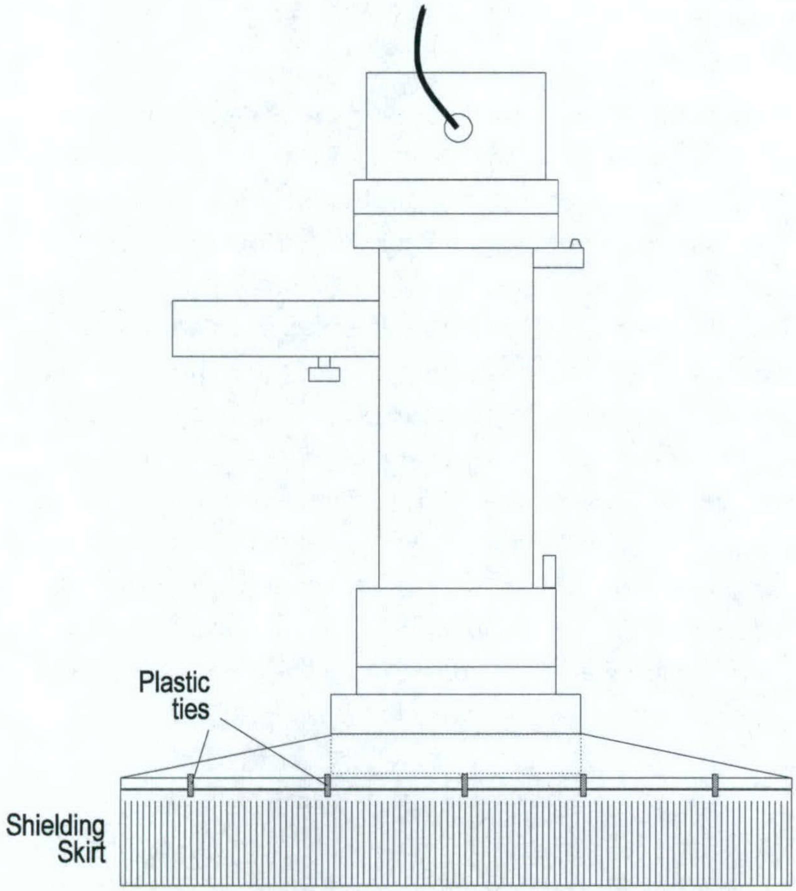


Figure 2. Modified applicator.

Microwave Paint Stripping Results from Laboratory Experiments

To prepare for the field demonstration of the microwave paint stripper on a window sill and/or trough, a mockup was constructed in parts to approximately realistic dimensions. One of the main concerns was the removal of paint from the troughs, especially the walls of the grooves. This would also help in obtaining important data on the microwave leakage levels in this more realistic application. The window frame dimensions were obtained from measurements made on a window in a building in Fort Lewis. The approximate dimensions of the window are shown in Figure 3.

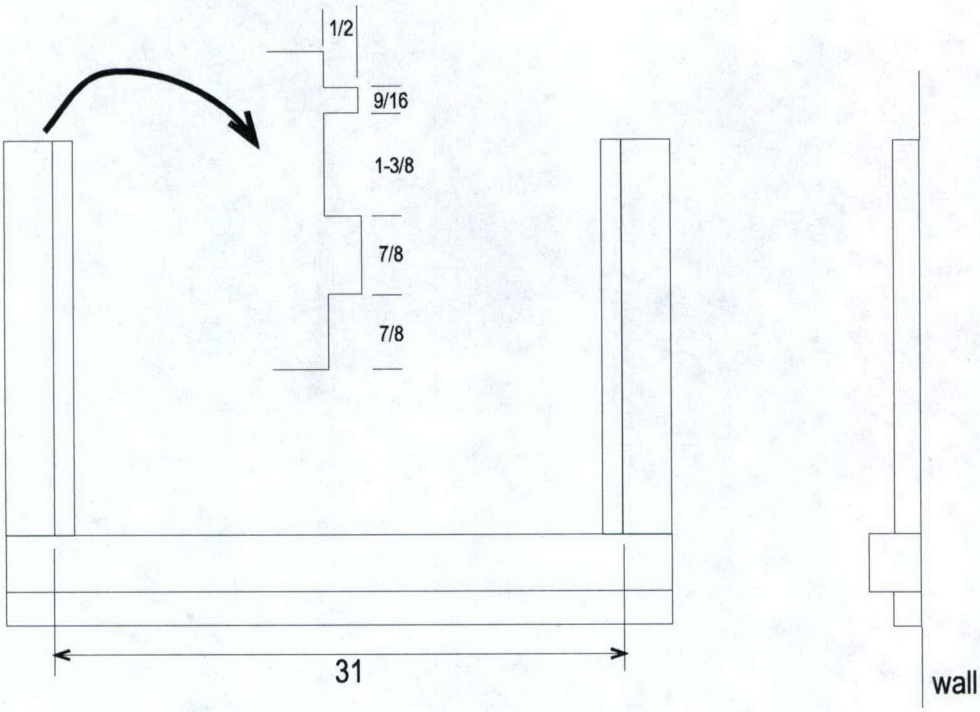
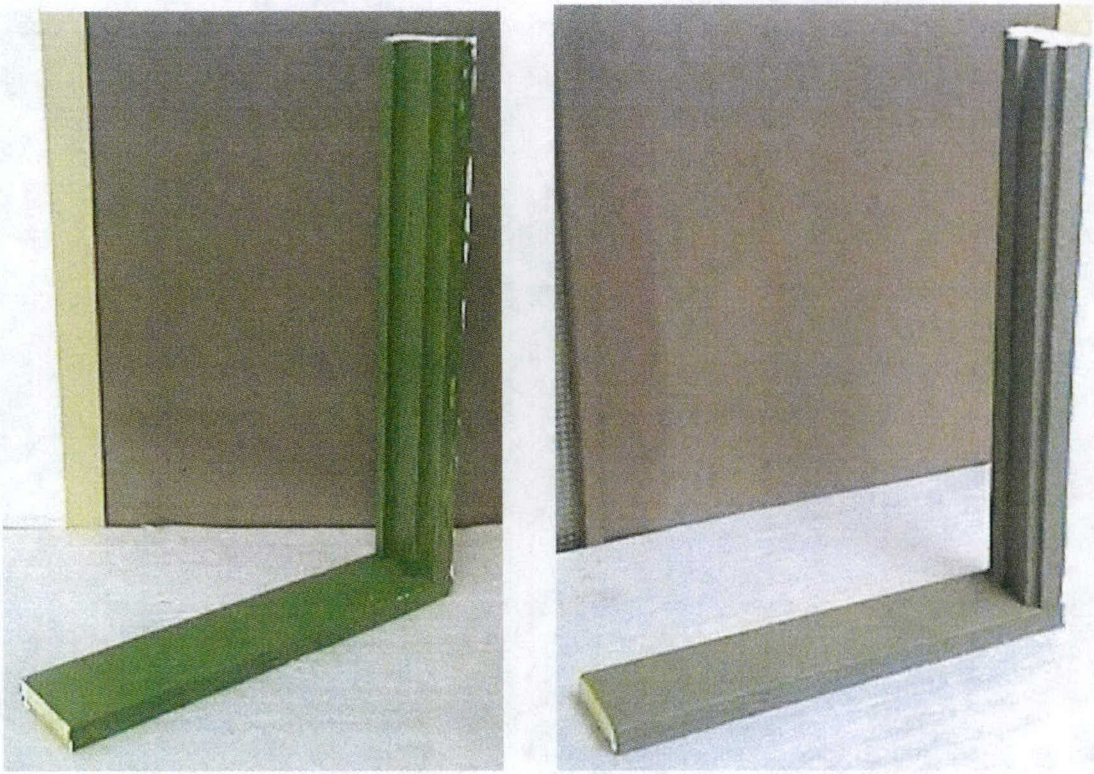


Figure 3. Approximate dimensions (inches) of the window frame.

Based on the dimensions of the trough section, an L-section containing the vertical trough and a horizontal sill was constructed. One coat of oil-based primer and two coats of a latex topcoat were applied and allowed to dry thoroughly. Figure 4a shows the painted L-section. Once the paint was completely dry, a thin coating (10 to 20 mils) of PreTox 2000® was applied using a brush. After the stabilizer coating was completely dry, a thin coating of the susceptor was applied over it as shown in Figure 4b.



a. Painted L-section b. Susceptor-coated section

Figure 4. L-section with original paint (left) and susceptor coating.

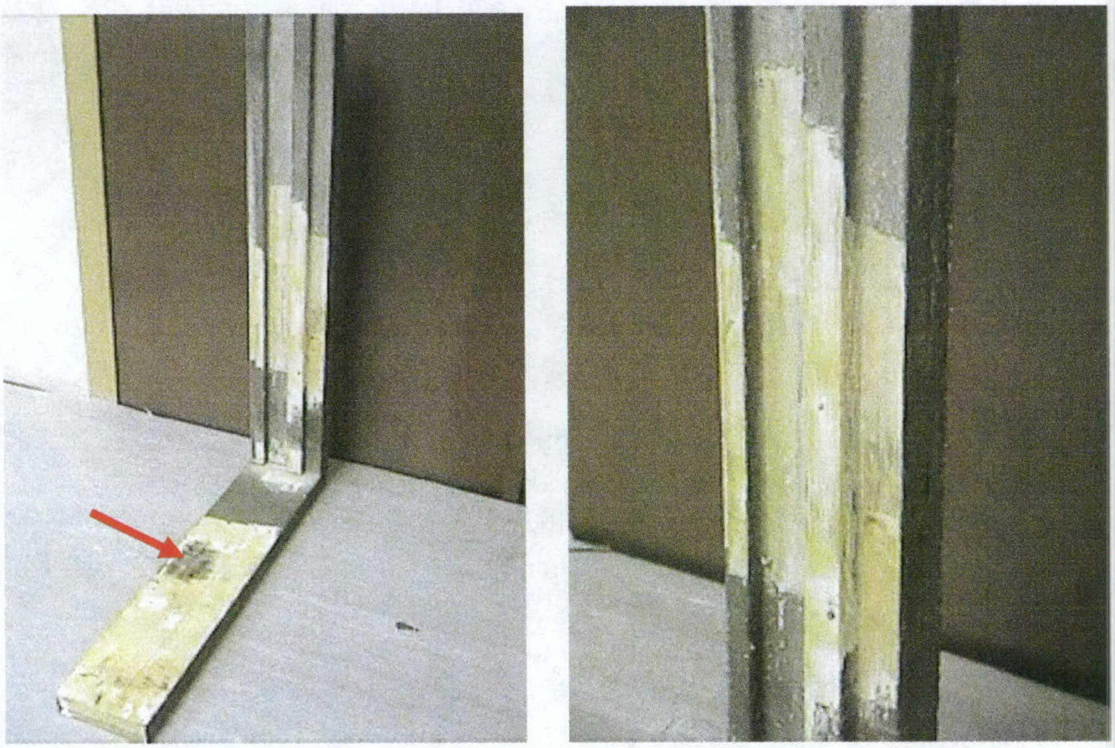
The resistance of the susceptor coating was measured after it was completely dry. The resistance measured in the vertical trough section is shown in Figure 5. Although the range of the measured resistance was from 87 to 240 Ω, the average resistance was well within 100 to 200 Ω.

120	220	165	240	165	120	95
150	135	140	195	240	170	126
207	215	165	185	145	158	120
186	135	87	175	130	97	145

Figure 5. Resistance (ohms) of susceptor measured on the vertical trough section

The HVS microwave paint stripper was used to strip paint first from the sill section and then from the trough section. The applicator was moved over a small portion of the area to be stripped in a scanning manner. After the susceptor heated up, a metal scraper was used to scrape the paint off the substrate. The applicator was held over one spot for a while to determine the effect on the substrate, and as can be seen in Figure 6a, there is a scorched mark on the substrate.

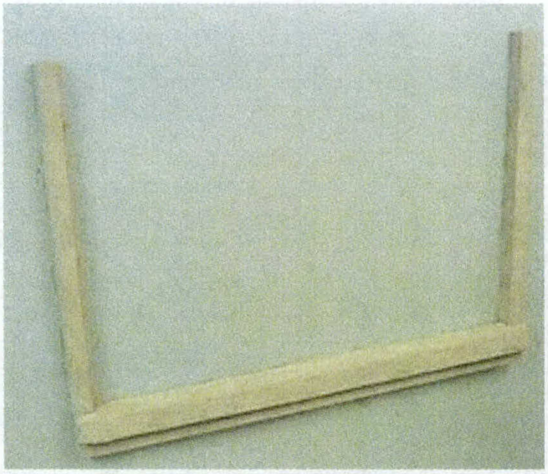
Figure 6b shows the close-up of the trough section where the paint was completely removed. This shows that the applicator is capable of heating the susceptor in these areas successfully.



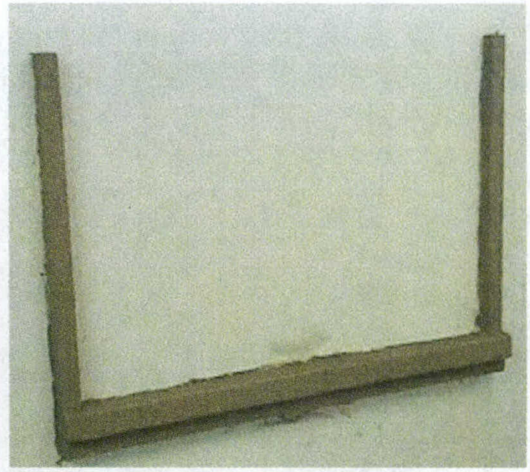
a. Scorched area b. Close-up of stripped trough section

Figure 6. Partially stripped L-section with close-up view (right).

As per the approximate dimensions shown in Figure 3, a mock-up window frame was built on a wooden wall. The main purpose of this setup was to test the ability of the applicator to heat the paint on the frame wall perpendicular to the wall into which the window frame is built. A U-shaped window frame was built and one coating of oil-based primer and two coats of a latex paint was applied on this section (Figure 7).



a. Stabilizer applied to section



b. Susceptor applied over stabilizer

Figure 7. Treatment of u-shaped window frame.

After the paint was thoroughly dry, a thin coating (10 to 20 mils) of the stabilizer (PreTox 2000®) was applied with a brush as shown in Figure 7a. The graphite susceptor was then applied to the dry stabilizer as shown in Figure 7b. The vertical sections represent the troughs and the horizontal section is the window sill. The thickness of this entire section represents the approximate amount the actual window frame projects from the building wall.

Figure 8 shows the close-up of the stripped area from one of the vertical sections. This again shows that the applicator can heat the paint even though the surface is not normal to direction of microwaves. Here again, the applicator was scanned relatively quickly but repeatedly over the same area. This not only prevents the susceptor from getting too hot and arcing, but also preheats the substrate so that the paint remains hot long enough for it to be scraped.

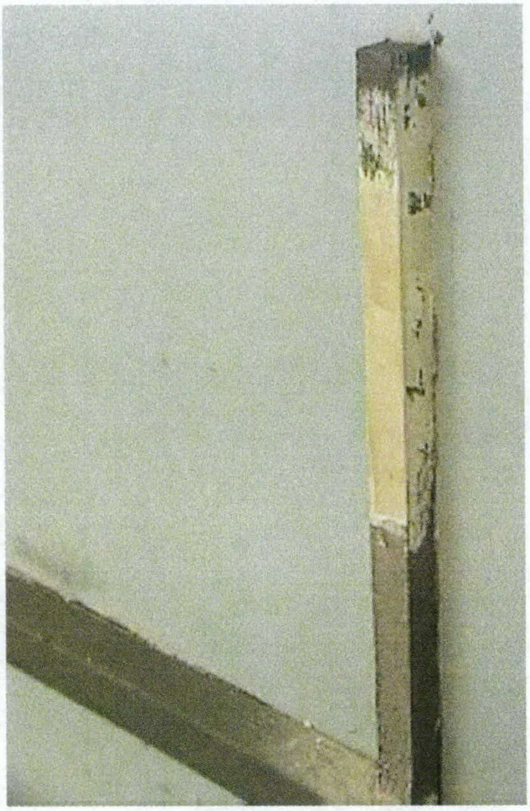


Figure 8. Paint stripped from a section adjacent to the wall.

These structures were made using nails 1-1/2 in. long with 1/8 in. diameter heads. The stabilizer and susceptor were applied on top of the nails, and during the stripping process using the microwave applicator, no noticeable arcing occurred around the nails. During the stripping process, microwave leakage was monitored and was found to be well within acceptable levels.

3 Demonstration Design

Performance Objectives

The performance objectives of this demonstration were as follows:

- Remove existing LBP.
- Comply with environmental standards.
- Comply with worker health and occupational safety requirements.
- Determine performance of the microwave-assisted paint removal process.
- Conduct cost and benefits assessment.

Selection of Test Site

A wooden window sill and trough coated with LBP was selected in an abandoned building at Fort Lewis, WA, slated to be destroyed were selected for testing. The building and window frame are typical of construction prior to 1978, where LBP was used.

Test Site Characteristics

The window sill and trough were found to be coated with eight layers of LBP, 24 mils thick, as analyzed by x-ray fluorescence (XRF) measurements. Figure 9 shows the building and window. X-ray fluorescence measurements (EPA 1991) were made on the window to ensure the presence of LBP. The microwave-assisted paint stripping demonstration was carried out on the horizontal sill and the vertical troughs of the window frame.

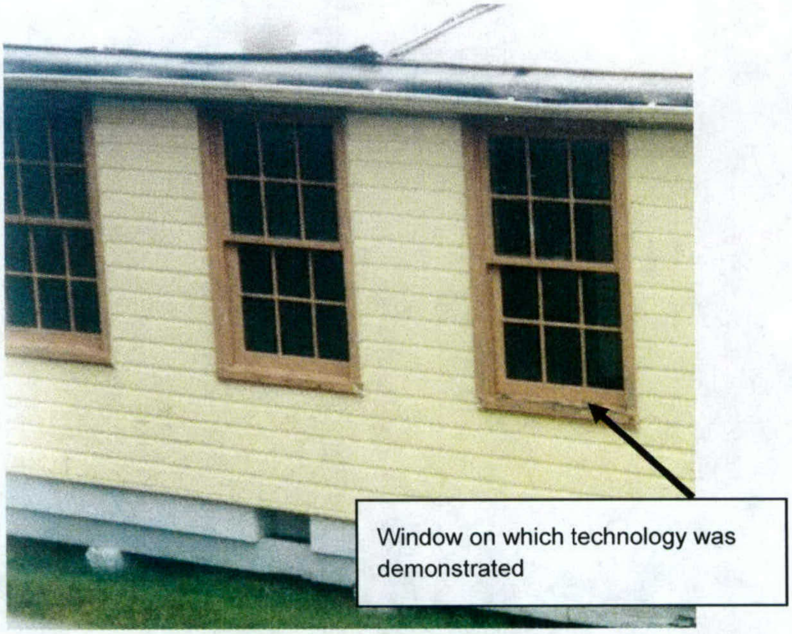


Figure 9. Window selected for field testing at Fort Lewis

Equipment and Test Setup

The equipment used during this field demonstration consisted of the following:

- a custom-designed microwave generator
- a microwave applicator with shielding skirt applicator, which was connected to the generator by a coaxial cable
- a wet/dry vacuum cleaner suction device connected to the applicator for collecting lead dust during operation
- a personal air monitoring device
- an airborne lead monitoring device (discussed in more detail in Appendix A).

Figure 10 shows the equipment as it was set up and used during the demonstration. The development and operation of the microwave generator and applicator have been described in Chapter 2.

The XRF measurements were carried out by Hart Crowser, Inc., Seattle WA, with a Niton XL-309 Spectrum Analyzer Lead Detector, which uses radioactive cadmium 109 (strength 10 mCi) as the source. (XRF measurement data are presented in Chapter 4, Table 1.) Figure 11 shows the XRF device being used to measure the lead levels on the window sill prior to microwave-assisted paint removal.

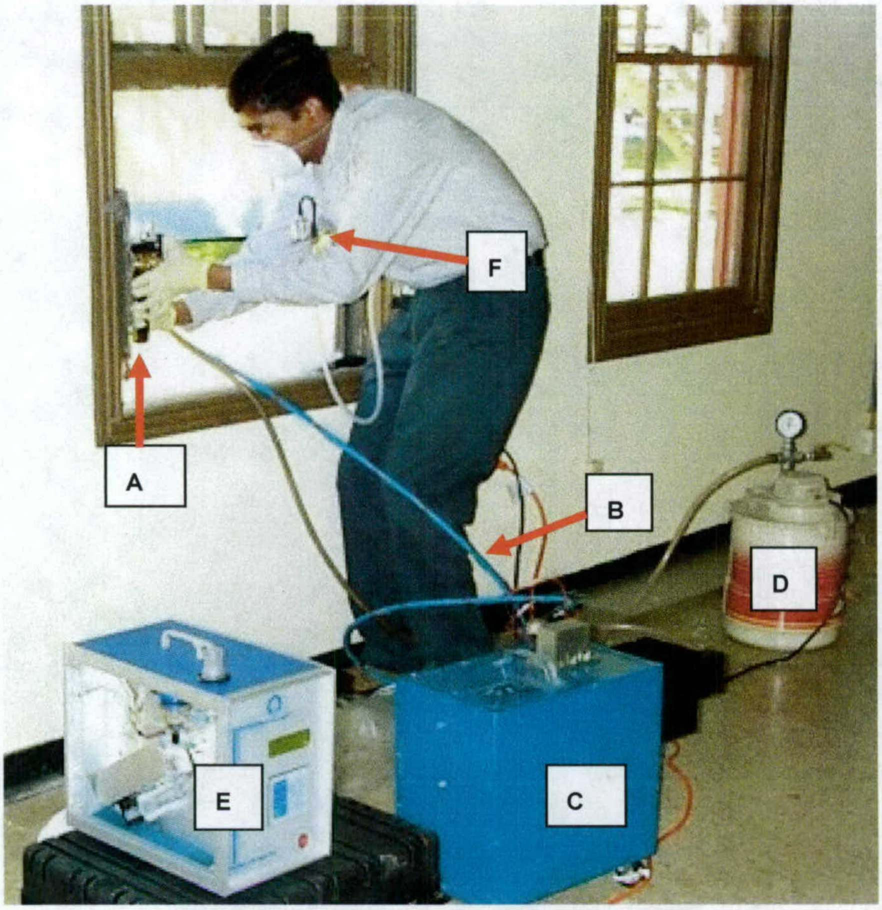


Photo key: A=microwave applicator, B=coaxial cable, C=microwave generator, D=suction device for microwave applicator, E=airborne lead dust monitor with left side removed, F= personal air monitoring device.

Figure 10. Equipment used in field demonstration.

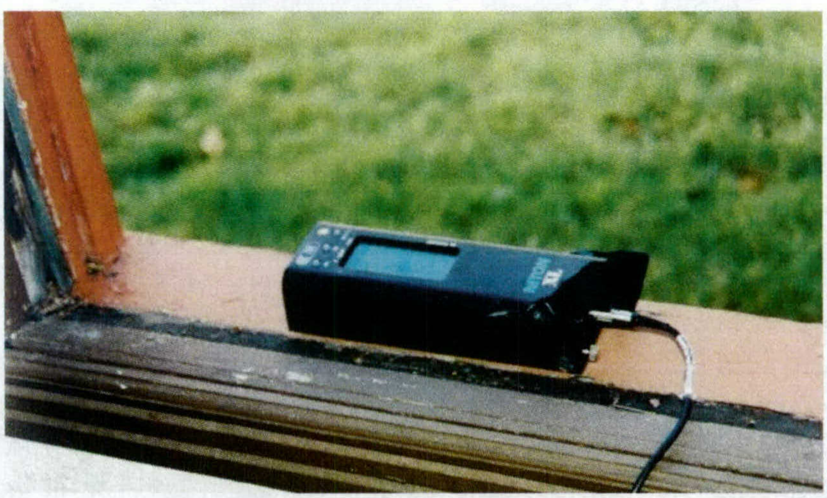


Figure 11. XRF measurement on window frame prior to removal of lead-based paint.

Prior to the start of the paint removal process, plastic sheets were spread out on the floor inside and outside the window to collect the paint and stabilizer debris. The resulting debris was subjected to the Toxicity Characteristic Leaching Procedure (TCLP) (40 CFR, Part 261) to determine the quantity of leachable lead.

Field Test Operations

A field test of microwave paint stripping was performed on the window frame shown in Figure 9. The area chosen to be stripped was the window sill and troughs. Although the frame contained metal nails, it was not considered a problem for causing arcing, as observed in laboratory experiments. Because the ambient temperature was in the range of 40 °F to 60 °F during the day, sufficient time had to be allowed for thorough drying of the stabilizer and susceptor coating. Hence the field demonstration was completed over a period of 3 days.

Day 1 (5 March 2001)

The selected window frame was thoroughly cleaned using a brush to remove dirt and paint chips. The stabilizer, PreTox 2000®, which is a cement-like substance, was thoroughly mixed for about 15 minutes using a stirrer connected to a drill press until the stabilizer appeared to be homogeneous. Before the stabilizer was coated, XRF measurements (EPA 1991) were carried out on the painted window frame to quantify the amount of lead present in the paint.

A thin coating of the stabilizer was applied with a paintbrush to the surface containing the LBP. Its application to the window frame took approximately 45 minutes. The window frame coated with stabilizer is shown in Figure 12.

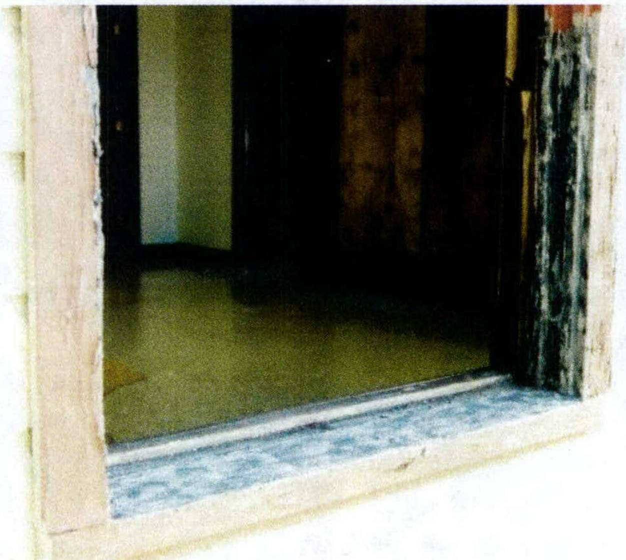


Figure 12. Window sill and trough coated with the stabilizer.

Since the window was exposed to the outside environment, it was necessary to protect stabilizer coated on the window from rain. To achieve this, a plastic sheet was nailed around the window on the outside. The stabilizer coating was left to dry overnight.

Day 2 (6 March 2001)

The stabilizer coating was inspected to ensure that it was completely dry. The susceptor, which is a mixture of latex paint, graphite powder, and distilled water, was stirred thoroughly until it had a homogeneous consistency. Because the susceptor is less viscous than the stabilizer, it is easier to apply. Again, a paintbrush was used to apply a thin coating of the susceptor over the stabilizer coating. The process of susceptor application is shown in Figure 13a, and the coated window frame is shown in Figure 13b.

a. application of susceptor

b. Window sill and trough coated with the susceptor

Figure 13. Application of the susceptor.

The susceptor coating was allowed to dry overnight, and as before, the window was covered with a plastic sheet nailed around it from the outside.

Day 3 (7 March 2001)

The resistivity of the susceptor coating was measured at various spots and observed to be in the range of 150 to 200 ohms. This is the ideal range for efficient heating of the LBP. If the resistivity is too low, the susceptor will just reflect the microwave energy without absorbing it. If the resistivity is too high, it will take a longer time for the microwave energy to heat the susceptor and subsequently the LBP.

Figure 14 depicts the process of paint removal from the window sill. Figure 14a shows the application of microwave power from the applicator to the window sill.

The microwave applicator was passed back and forth over a small area for about 8 seconds. Because the ambient temperature was about 50 °F, the microwaves were applied for a longer time for the paint to heat and soften. The shielding gasket skirt dropped down around the main gasket, as shown in Figure 14a, and thus prevented any microwave radiation getting out of the application area. This shielding provided adequate protection for the operator.

a. Heating the frame with microwaves

b. Scraping the heat-softened paint

Figure 14. Removal of paint from the window sill.

After the LBP was softened using the microwaves, a 1-in.-wide scraper was used to scrape the paint off the wooden substrate. The LBP was encapsulated in the stabilizer coated on it. Figure 15 shows the application of the microwave energy at a corner in the window frame. In this case, the microwave heating was carried out for about 20 seconds due to the greater gap between the opening in the applicator and the painted surface at the corner.

Figure 15. Application of microwaves to the window frame corner.

During the paint removal process, a microwave leak detector was used to determine if there were any radiation leaks. The data are discussed in Chapter 4.

Analytical Procedures

Personal air samples were analyzed by Hart-Crowser according to National Institute for Occupational Safety and Health (NIOSH) Method 7300 (NIOSH 1994). The respirable dust level was measured by NIOSH Method 600. TCLP was performed in accordance with EPA Method 1311 [40 CFR, Part 261].

4 Performance Assessment

The window sill and troughs were stripped of the LBP in about 2.5 hours. The stripped window sill and troughs are shown in Figure 16. It can be seen that there are a few small areas where the paint is still left. This is due to the inefficiency in the manual scraping process. After a particular area was heated by the microwaves and scraped, the operator may have inadvertently removed the susceptor coating in an adjacent area where the paint had not been heated and softened by the microwaves. Once the susceptor is removed with the paint still intact under it, it is impossible to remove the paint without recoating the stabilizer and susceptor. It is estimated that more than 90 percent of the LBP was removed from the window sill and troughs.

a. stripped window sill b. stripped corner

Figure 16. Window sill and trough after LPB has been removed.

After the LPB was stripped from the window, XRF measurements (EPA 1991) were again made at the same locations as before the paint was removed and the results were compared. The debris collected on the plastic sheets laid out by the window were collected and stored in plastic bags. This debris was subjected to a TCLP (40 CFR, Part 261) to determine if the scraped paint debris was nonhazardous and if it could be disposed off in a nonhazardous waste landfill.

Microwave Radiation Leakage Measurements

It was observed that the detected levels were less than 3 mW/cm^2. This is below 5 mW/cm^2 and considered safe by international standards, and below 8.2 mW/cm^2 which is the U.S. safety limit at 2.45 GHz (IEEE C95.1-1991 1992.)

XRF Measurements

The XRF measurements, described previously, were made at the spots shown in Figure 17 and the results are presented in Table 1.

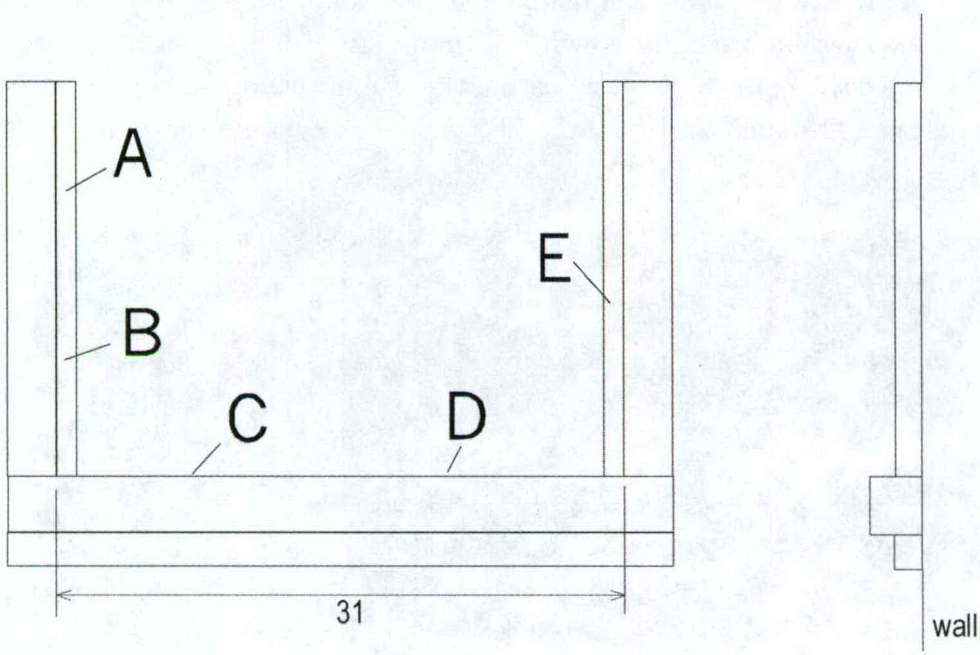


Figure 17. Locations of XRF measurements.

Table 1. Results of XRF measurements.

Measurement Location	Before LPB Removal (mg/cm^2)	After LBP Removal (mg/cm^2)
A	5.1	2.6
B	14	0.14
C	1.7	0.7
D	0.27	0.2
E	1.9	0.05

As can be seen from Table 1, the amount of lead present in the substrate decreased to less than 1 mg/cm^2, in most cases, as a result of LPB removal using the microwave-assisted technique. It should also be noted that the substrate was fully intact without any damage.

Toxicity Characteristic Leaching Procedure (TCLP)

A TCLP (40 CFR, Part 261) analysis of the paint scrapings was carried out by PDC Laboratories, Peoria, Illinois. The result for the TCLP for lead was 0.033 mg/liter. This value is much lower than 5 mg/L, which is the maximum allowable lead content for nonhazardous waste. Therefore, the scrapings of the LBP encapsulated in the stabilizer could be disposed in a regular landfill. The chemical stabilizer used in the lead abatement renders the LBP nonhazardous, thus saving the expenses associated with the handling and disposal of hazardous wastes.

Technology Comparison

Current removal methods for hazardous paint that contains lead, chromium, or cadmium all have some shortcomings. This includes chemical stripping, abrasive blasting, vacuum-assisted power tools, and other heating process, such as heat gun and high-intensity xenon lamps. The microwave-assisted paint removal process provides several advantages of the conventional LBP removal methods:

- The wooden substrate is not damaged as in abrasive blasting or using power tools.
- The microwave applicator does not expose wooden substrates to high temperatures that may cause a fire, in contrast to the use of heat gun.
- The lead paint debris is nonhazardous and can be disposed in a nonhazardous landfill.
- The amount of lead dust produced is low compared to removal by power tools or abrasive blasting.
- No toxic chemicals are required in contrast to chemical stripping,
- No containment is required in constrast to abrasive blasting.

The microwave-assisted LBP removal process, however, requires the use of specialized equipment that is currently available only from a small number of vendors. Also, the coatings to be removed must be overcoated with susceptors and chemical stabilizers prior to application of the microwaves. Both of these materials are applied in a wet state requiring several hours to dry, in contrast to blasting, power tools, or heat guns. Finally, scraping is required, which can be slower than power tools and blasting.

5 Cost Assessment

This chapter describes the production rate and cost analysis for the microwave-assisted LBP removal process as demonstrated at Fort Lewis and projects how the technology may be improved beyond the current practice. Although the entire process at Fort Lewis was carried out over a period of 3 days because the susceptor and chemical stabilizer had to dry overnight due to ambient low temperatures, only the actual time contributing to labor costs is considered for this analysis.

Area from which the LBP was removed and amount of stabilizer and susceptor used were calculated as follows:

- Width of the window frame from which LBP was removed = 31 in.
- Height of the window frame from which LBP was removed = 22.5 in.
- Area of the window sill = 31 in. x 3.69 in. = 114.3 inch^2
- Area of each trough = 22.5 x (0.875 + 0.5 + 0.875 + 0.5 + 1.375 + 0.5 + 0.5625) = 116.7 inch^2
- Total area from which LPB was removed = 114.3 + 2 x 116.7 = 347.7 inch^2 = approx. 2.5 sq ft/window sill and trough
- Amount of PreTox 2000® (stabilizer) required = 347.7 in. x 40 mils (thick) = 13.9 in^3
- Amount of susceptor coating required = 347.7 x 5 mils (thick) = 1.74 in^3

Time taken for the LPB removal was calculated as follows:

- Actual time using the microwave-assisted stripper = 2 hr.
- Total time included in computation of labor costs = 5 hr (this accounts for stirring, application of coating chemicals, etc.)

This removal rate is 1.25 sq ft/hr (2.5 sqft/2 hr); however, it is projected that with practice, a skilled operator can increase the removal rate by 30 percent, up to 1.625 sq ft/hr.

Thus, if the process is applied to 40 windows at 2.5 sq ft per window (100 ft^2), the costs in the following discussion are based on a removal rate of 1.625 sq ft/hr:

Time required to remove LBP from 40 windows = 62 hr microwave heating and scraping time and 7 hr surface preparation. It is assumed that the assistant laborer will perform surface preparation (apply susceptor and chemical stabilizer), and assist with paint scraping.

Other assumptions are as follows:

- Cost of 13.9 in.^{3} of PreTox 2000® (stabilizer) = \$82 (based on \$34.15/gallon)
- Cost of 1.74 in.^{3} of susceptor (latex paint + graphite + water) = \$10 (estimated)
- Cost of electricity for microwave-assisted stripping of LBP.
  total power required = 2 kW (for microwave system and vacuum system, used 40 percent of the removal time) cost = (0.4 x 62 x 2) kWhr x \$0.12/kWhr = \$5.95
- Labor cost (assuming 32 hr @ \$35/hr for a foreman and 37 hr @ \$15/hr for a laborer = \$3,343

Other cost details are given in Table 2 below.

Based on the results of this demonstration, the total cost for the removal of LBP from a typical window sill and trough is projected to be \$33.43 per sq ft. However, technological improvements in the *in situ* microwave-based paint removal process that will make it more cost-effective are expected. Furthermore, the use of susceptors and chemical stabilizers may be adapted to an innovative process that uses industrial microwave ovens to remove paint from window components that can be removed from the buildings.

In a LBP removal process currently used by the historical preservation and restoration industry in the United States, window sashes with glazing are removed from their buildings, and the paint is removed using a chemical stripping process in a trailer onsite. However, in some European countries, industrial microwave ovens that can accommodate entire windows are being used for lead-based paint removal. (Appendix B). These ovens provide homogeneous heating to soften the lead-based paint and the putty holding the glazing within 20 minutes. The windows are then removed from the microwave ovens, and the glazing is removed. The softened paint is easily removed by scraping from both sides of the window sash.

Table 2. Costs for microwave-assisted LBP removal process for 40 typical window sills and troughs (100 sq. ft.) based on demonstration results at Fort Lewis, WA.

Activity	Time/Cost	Activity	Time/Cost	Activity	Time/Cost
Startup		Surface preparation and Paint Removal		Demobilization	
Rate per hour (Foreman)	$35	Rate per hour (Foreman)	$35	Rate per hour (foreman)	$35
Hours	1	Hours	32	Hours1	1
Rate per hour (Laborer)	$15	Rate per hour (Laborer)	$15	Rate per hour (laborer)	$15
Hours	1	Hours	37	Hours	1
Total Hours	1.5	Total Hours	69	Total Hours	1.5
Labor Subtotal	$50	Labor Subtotal	$1,675	Labor Subtotal	$50
Other costs	$24	Consumables (Susceptor and chemical stabilizer)	$92		
		Equipment Depreciation (10 years, 60%)	$10		
		Waste transportation and disposal (nonhazardous)	$4		
		Electric power	$5.95		
Overhead on labor @15%	$7.50	Overhead @15%	$251	Overhead @15%	$7.50
Category Total	$58	Category Total	$2,038	Category Total	$58
Subtotal all categories					$2,153
General & Admin Overhead @ 35%					$754
Subtotal					$2,907
Profit @ 15%					$436
TOTAL for 40 windows					$3,343
Cost/window					$83.57
Cost ($/sq ft)					$33.43

As an alternative to chemical stripping, the microwave oven paint stripping process is about 39 percent faster because chemical strippers are slow acting and may require several applications. All work can be performed onsite, as the microwave ovens can be transported in a trailer, and electricity for operation of the ovens can be supplied by a generator transported to the work site.

Other differences in the processes include the following:

- Chemical stripping: This process is more labor intensive; cost of chemical stripper and neutralizer materials must be included; hazardous waste must be disposed at a hazardous waste site. It takes longer to remove the glazing as the putty is very hard, and it takes longer to remove the lead-based paint by chemical strippers, because it is a relatively slow process.
- Industrial microwave oven: Electricity to operate oven must be included in the cost, along with susceptor and chemical stabilizer materials; nonhazardous waste can be disposed at a nonhazardous waste site.

Consider a large window measuring 5 ft by 6 ft (inner frame dimensions), with wooden sashes and mullions whose surface area is 10 sq ft per side; i.e., a total of 20 sq ft of wooden surface from which LBP must be removed.

For a cost comparison, the following assumptions are made, based on European experience:

- Fifty of these window sashes are subjected to the microwave oven process: to remove LBP from a total of 1,000 sq ft of wooden surface area.
- It takes 20 minutes to heat the window sashes by microwaves at 3 kW.
- Glazing and paint removal require 40 minutes.
- The window sash is repainted in 20 minutes. Glazing replacement requires 20 minutes. Window removal and replacement processes require 66 minutes each. Thus, a total time of 233 minutes (3.8 hr) is required for each window.
- Susceptors and chemical stabilizers are used to improve the efficiency and reduce the hazardous waste.

The cost analysis for removing LBP from 50 windows of this type is given in Table 3.

Table 3. Costs for microwave-assisted LBP removal process using industrial microwave oven for 50 windows (1,000 sq ft).

Activity	Time/Cost	Activity	Time/Cost	Activity	Time/Cost
Startup		Surface preparation and Paint Removal		Demobilization	
Rate per hour (Foreman)	$35	Rate per hour (Foreman)	$35	Rate per hour (Foreman)	$35
Hours	2	Hours	233	Hours	2
Rate per hour (Laborer)	$15	Rate per hour (Laborer)	$15	Rate per hour (Laborer)	$15
Hours	2	Hours	233	Hours	2
Total Hours	4	Total Hours	466	Total Hours	4
Labor Subtotal	$100	Labor Subtotal	$11,650	Labor Subtotal	$100
Other costs		Consumables (Susceptor and chemical stabilizer)	$920		
		Equipment depreciation (10 years, 60%)	$10		
		Waste transportation and disposal (nonhazardous)	$38		
		Electric power	$12		
Overhead on labor @15%	$15	Overhead @15%	$1,748	Overhead @15%	$15
Category Total	$115	Category Total	$14,377	Category Total	$115
Subtotal all categories					$14,607
General & Admin Overhead @ 35%					$5,113
Subtotal					$19,720
Profit @ 15%					$2,958
TOTAL (for 50 windows)					$22,678
Cost/window					$453.56
Cost ($/sq ft)					$22.68

Thus, use of the microwave ovens to remove LBP from the window components is projected to cost $22.68 per sq ft. If the chemical stripping process is used, it is assumed that the entire procedure will take about 3 hr longer because of the reduced reaction time of the chemical stripper, and the difficulty in removing the hard putty to remove the glazing. The costs of the alternative chemical stripping process are given in Table 4.

Table 4. Costs for currently used chemical stripping process for 50 windows (1,000 sq ft).

Activity	Time/Cost	Activity	Time/Cost	Activity	Time/Cost
Startup		Surface Preparation and Paint Removal		Demobilization	
Rate per hour (Foreman)	$35	Rate per hour (Foreman)	$35	Rate per hour (Foreman)	$35
Hours	2	Hours	380	Hours	2
Rate per hour (Laborer)	$15	Rate per hour (Laborer)	$15	Rate per hour (Laborer)	$15
Hours	2	Hours	380	Hours	2
Total Hours	4	Total Hours	760	Total Hours	4
Labor Subtotal	$100	Labor Subtotal	$19,000	Labor Subtotal	$100
Other costs		Consumables (Chemical stripper)	$200		
		Waste transportation and disposal (nonhazardous)	$60		
Overhead on Labor @15%	$15	Overhead @15%	$2,850	Overhead @15%	$15
Category Total	$115	Category Total	$22,110	Category Total	$115
Subtotal all Categories					$22,340
General & Admin Overhead @ 35%					$7,819
Subtotal					30,159
Profit @ 15%					$4,524
TOTAL for all 50 windows					$34,683
Cost/window					$693.66
Cost ($/sq ft)					$34.68

Thus, the cost of the microwave oven-based LBP removal process is projected to be $22.68 per sq ft, compared with $34.68 per sq ft (for chemical stripping), resulting in a cost saving of $12 per sq ft, or 35 percent over the chemical stripping process.

If the *in situ* LBP removal process used in the technology demonstration at Fort Lewis can be further developed to achieve the higher heating efficiency of the industrial microwave ovens, with appropriate microwave shielding, additional cost savings could be realized. The LBP could be removed in a shorter time interval than in the Fort Lewis demonstration, e.g., in 1.7 hr per window, without having to remove the window sashes. This would reduce the process time by 2.1 hr. The total cost would be $10.80 per sq ft. This represents a cost savings of $23.88 (69 percent) over the chemical stripping process.

6 Implementation Issues

Implementation Costs

Several factors influence the cost and performance of the microwave-assisted paint removal process: number of layers, thickness, and relative adhesion of paint. The complexity of the substrate also negatively influences the productivity of the process. Substrates with crevices, bends, corners, and recessed areas are more difficult to access and require additional time for processing.

As stated in the previous chapter, the cost of the microwave oven-based LBP removal process is projected to be $22.68 per sq ft, compared to $34.68 per sq ft (for chemical stripping), resulting in a cost saving of $12 per sq ft, or 35 percent over the chemical stripping process. If the *in situ* LBP removal process can be further developed to achieve the higher heating efficiency of the industrial microwave ovens, with appropriate microwave shielding, additional cost savings could be realized. It is projected that for this case, the paint removal time would be reduced by 2.1 hr. The total cost would be $10.80 per sq ft. This represents a cost savings of $23.88 (69 percent) over the chemical stripping process.

Performance Observations

The microwave LBP removal process was conducted on a surface of complex geometry, viz., a window sill and trough. The lead dust was reduced to levels that permit the process to be performed without containment. Because the exposure levels are less than for other processes (e.g., abrasive blasting), the protection required for workers is also reduced.

The waste from the process was rendered nonhazardous by the use of chemical stabilizers, and thus can be disposed in a nonhazardous waste site. In this demonstration, the microwave-assisted LBP removal process produced approximately 900 grams of nonhazardous waste for each square foot of LBP removed; however, this can vary considerably, depending on the number of layers of LBP on the substrate. Usually, the paint is removed so that lead levels are reduced to less than 1 mg/cm^2, and the stripped substrate is suitable for repainting.

The microwave LBP removal process is suitable for removal of LBP from doors and window frames. Flat substrate geometries are easier and require less time for removal of LBP.

Other Significant Observations

During the demonstration, it was noted that after a particular area is heated by the microwaves and scraped, the operator may inadvertently remove the susceptor coating in an adjacent area where the paint has not been heated and softened by the microwaves. Once the susceptor is removed with the paint still intact underneath, it is impossible to remove the paint without reapplying the stabilizer and susceptor. This appears to have occurred at several spots in the window trough on which the microwave-assisted LBP removal process was demonstrated.

Regulatory Issues

The principal regulatory issues involve the protection of the environment and the worker during LBP abatement. The principal regulatory drivers are the following: (1) Clean Air Act (CAA) and the 1990 CAA Amendments, including the National Emission Standards for Hazardous Pollutants (NESHAPS), (2) Clean Water Act (CWA) of 1977 as amended with the National Pollution Discharge Elimination System (NPDES) Permit Regulations, and (3) RCRA. The principal regulatory driver to protect workers during LBP abatement are: (1) Title 29, CFR Pat 1910, Occupational Safety and Health Administration, "Safety and Heath Regulations for Construction", Part 1926.

Lessons Learned

The microwave-assisted paint removal technology was validated for removal of LBP on wood.

Calcium silicate based chemical stabilizers such as PreTox 2000® can be applied to the LBP along with the susceptor to render the debris nonhazardous (i.e., that leaches less than 5 ppm lead by the TCLP). The chemical stabilizer should be in the form of a liquid paste that can be brush applied directly on top of the LBP.

A graphite-based susceptor in the form of a wet slurry must be overcoated directly onto the chemical stabilizer. After being allowed to dry for several hours, the susceptor must have a resistivity on the order of 160 ohm-cm. This resistivity will ensure efficient coupling of the microwaves with the LBP for proper heating to temperatures of about 90-100 °C, so that the paint is sufficiently softened for easy removal by scraping.

Using the microwave applicator, paint removal rates vary depending on the thickness and number of layers of paint. Production rates range from 1.2 sq ft /hr to 2 sq ft/hr for a complex surface, such as a window sill and trough, to 3 sq ft/hr for a flat surface, such as a door.

A variation on the technology demonstrated here has been developed independently by entrepreneurs in Sweden and Denmark. The European variation entails removal of the window from the building, and placing it into an industrial microwave oven. The LBP can be removed by simple heating or by pyrolysis, where a susceptor is coated on top of the paint to be removed as in the *in situ* process. It is believed that the moisture in the wood contributes to the heating process for removing the LBP in cases where the susceptor is not used.

It is anticipated that the microwave-assisted LBP removal can be used by the historic preservation market for removal of paint from architectural components, such as windows and doors in historic buildings, where blasting and power tools would destroy fine wood surfaces.

Size of Potential U.S. Market

Lead-based paint was widely used in North America on both the exteriors and interiors of buildings until well into the second half of the twentieth century. If a "historic" place is broadly defined in terms of time as having attained an age of 50 years, this means that almost every historic house contains some LBP. In its deteriorated form, LBP produces paint chips and lead-laden dust particles that are a known health hazard to both children and adults. Lead-based paint was used extensively on wooden exteriors and interior trimwork, window sash, window frames, baseboards, wainscoting, doors, frames, and high-gloss wall surfaces such as those found in kitchens and bathrooms. Even milk- (casein) and water-based paints (distemper and calcimines) could contain some lead, usually in the form of hiding agents or pigments. Varnishes sometimes contained lead. Lead compounds were also used as dryers in paint and window glazing putty (Park and Hicks 1995).

In 1992, Federal Title X legislation (Public Law 102-550) mandated the disclosure of lead in residences, even private residences, prior to sale. Resale liability related to lead had a direct impact on the historic preservation market and is now a risk for the real estate industry. This newly identified risk prompted exploration of new means and methods of lead abatement.

Microwave Application Status In Sweden and Denmark

The use of microwaves for paint stripping was introduced in Denmark in 1994 when the company Nordahl & Axelsen A/S obtained a license agreement for a Swedish patent (SE470255 / EP0629157). According to this patent, windows to be stripped are heated in a large microwave oven and subsequently the softened paint is scraped off. This process is based on the phemonenon of microwaves agitating water molecules, as in the traditional household microwave ovens. The process thus requires that the wood contain a certain amount of humidity (approximately 20 percent according to SE patent 470255 (Swedish Patent No. WO9317882, Haakansson 1993).

In 2002 a newly established company, WoodTech ApS, started production according to a new method developed and patented by U.S. Army Construction Engineering Research Laboratory (U.S. patent 5268548, Kumar 1993). According to this method, slurry of graphite is applied to the article before it is inserted into the oven and exposed to the microwaves. A coat of stabilizer may be applied prior to the coat of graphite slurry, but such a stabilizer is not used in Denmark. When exposed to microwaves, the graphite will start to glow whereby the coat of paint is pyrolized (Ellgaard 2002).

Visits to Successful Vendors of Microwave Paint Removal In Sweden and Denmark

From 23-27 August 2002, a visit was made to Scandinavia to examine firsthand the current technology for microwave paint removal. Visits to facilities in Denmark and Sweden provided the opportunity to view the process and the equipment required for the use of this new stripping technology. It was also determined that visits to equipment manufacturer facilities would be useful because the stripping ovens are custom built.

The first meeting was an interview with Jorgen Ellgaard of Virkon, a design, fabrication, and consulting contractor. The result of this meeting was to arrange an interview with Jesper Jensen, Managing Director of TORA Maskinfabrik of Kolding, a fabricator; Eric Piil, Managing Director of IMITEC of Nyborg, an industrial microwave technology engineer; Dr. Ashok Kumar; Mr. Ellgaard; and Mr.Thomas Tisthammer, Division Seven Systems, on August 26. Although TORA obviously had the fabrication capacity and had built one stripping oven 2 years before, the 26 August meeting determined that TORA's effort would be unnecessary for a U.S. pilot project. At the conclusion of the meeting, Mr. Piil of IMITECH agreed to deliver a quote for a finished oven of the configuration desired.

Dr. Kumar was able to arrange a meeting later in the week in Sweden with another oven fabricator, GISIP AB. On 28 August, a meeting was conducted at the GISIP facility where discussions were held with Goran Gustafsson, Managing Director and Per-Erik Gustafsson, Director of Research and Development. GISIP's primary business is supplying microwave technology used for the drying of wood and paper products. During this meeting, a list of technical requirements was developed to use as an evaluation guide for future proposals by equipment suppliers. At the conclusion of the meeting, Mr. Gustafsson of GISIP agreed to deliver a quote for a finished oven with the desired configuration.

On 29 August, Dr. Kumar, Goran Gustafsson, and Thomas Tisthammer traveled to Ryd, Sweden, to meet with Goran Haakansson, Managing Director of BYGGSAM, AG and his staff. The purpose was to view his facility and equipment and witness a demonstration of the microwave stripping process. Mr. Haakansson holds the Swedish patent (Swedish Patent No. WO9317882, Haakansson 1993) for the use of microwave technology for use in the stripping of paint from various surfaces. Hakaansson's operation was very professional and his facilities were well maintained. He has been using the microwave technology for several years and has done a large number of jobs. BYGGSAM is currently working with the Wood Industrial Development Center at Olofstrom and the Kronoberg Technical Center to optimize the microwave stripping process, and to document the effects of microwave radiation on the physical properties of wood products.

After a tour of the facility, Haakansson selected a painted 24-in. by 24-in. window sash, complete with glazing, and inserted it into the microwave oven. It remained exposed for approximately 1 minute, after which it was removed by hand and placed on the worktable. It was very warm to the touch but not hot enough prevent its being handled by a bare hand. A rolling scraper was used to remove the old putty, which had now become very soft and pliable, although it did not run or slump. The putty came away in one piece, clean and in long strips, from the glass, wood, and glazing point surfaces. The glass was not warm to the touch and showed no evidence of heating. Removal of all putty took about 2 minutes. Once the putty was removed, the glass panes were removed quickly and easily without breakage. Next, a two-inch wide Sandvik paint scraper was used to remove the paint from the sash surfaces. Firm pressure and a smooth, steady downward stroke pulled the paint cleanly away from the heated wood surface. Depressions in the wood surface and the mullions must be scraped with an appropriately shaped scraper, but the paint is soft enough to be removed by a shaped hardwood dowel or stick without damage to the sash. During the heating process, sap came to the surface in a softened, semi-liquid state. It was easily wiped/scraped off. It might be wise also to wipe the warm surface with turpentine or the appropriate solvent to prevent bleed-through after repainting. Total time for the removal of putty, glazing, and all the paint was about 10 minutes. The sash had cooled somewhat but was still warm. At this point, the paint removal process was complete and the window was ready for further restoration work that might be required.

Visits were arranged to two historic building sites on which the microwave paint removal process had been used to restore existing window sashes. One project, renovation of a 300-year-old parsonage, was completed 9 years ago. The other, a 100-year-old museum/library, was treated approximately 4 years ago. Careful examination gave no evidence of unusual conditions that might have resulted from the use of microwave stripping as opposed to conventional methods. Some evidence of sap bleed-through was noted, but it was not extraordinary for this type of work. The wood grain remained tight, as did the joinery. Paint was stable and glazing was intact with weathering of all surfaces typical of their age and exposure. General overall surface quality was better than typical restorations done by chemical or high temperature means.

Paint Removal Tools Currently In Use

Hand tools currently in use are standard paint removal and glazing tools. A major manufacturer of tools of this type is Sandvik, a Swedish company whose tool line is available in the United States. An interesting movable worktable or jig was in use for the clamping and subsequent scraping of the window sashes. It was constructed of aluminum, stood waist-high, and allowed the sash to first be fixed in place and then rotated to virtually any position relative to the worker. The softened glazing putty was removed using the previously mentioned rolling scraper, a common glazing tool.

In Situ Microwave Paint Stripping Device For Doors and Windows (Elements)

In Sweden and Denmark, microwave paint stripping activities are currently restricted to in-plant operations, in which the windows are removed from their buildings and treated ex situ. Although previous efforts to construct portable devices have shown limited success (Booth et al. 1999), the problem of shielding the work area and surrounding environment from microwave radiation has proven to be the main obstacle to *in situ* microwave paint stripping activities. It should be emphasized that no matter how simple and safe the proposed device may be, its operation should be allowed only by thoroughly trained personnel. These personnel must be certified to handle LBP and the resulting debris, and be familiar with all appropriate workplace safety regulations, and the proper use of the microwave machinery.

Since a primary component of historic preservation efforts is the restoration of doors and windows and since these elements (exclusive of the movable sashes) often must remain in place, there is a demand for field treatment of these items. Exterior windows and doors have frames both inside and outside the building while interior units have only interior surfaces. Microwaves directed at any of these surfaces may penetrate the walls into adjoining rooms and hallways or pass through to the outside of the building and therefore must be contained. Shielding for microwave exposure is relatively simple by using metal screens whose perforations do not permit the passage of the emitted wavelength. Shielding must keep microwave emissions below 5 mW/cm^3 at a range of 5 cm as specified in IEEE C95.1 (IEEE 1992). Small microwave ovens (with the volumetric capacity of a single window sash) have been constructed and proven effective for paint removal while meeting emission requirements. Given this success, it follows that a similar device could be constructed that could be easily assembled around in-place elements to be treated. Such a device, depicted in Figure 18*, has the following features:

- A metal enclosure in two halves that can be assembled around the element, one side contains the microwave generator and shielding, the other side is made up of additional shielding enclosing the other side of the element.
- A clamping system that holds the unit in place through the element opening, "sandwiching" the element between the two halves of the enclosure.
- An appropriate power supply and microwave leakage detector.

Treatment of window frames would expose one side of the element at a time. After one side was stripped of paint, the unit would be removed and reassembled in a mirror image position to treat the remaining side. This would allow work to be performed either inside or outside the building as scheduling permitted. The unit would be fitted with leakage detectors that would have a 'deadman' function. If

* Provided for this study by Thomas Tisthammer, Division Seven Systems, Bellevue, CO, November 2002.

leakage is detected, the magnetron unit automatically locks out of operation until properly installed around the element. Research on this device is in progress.

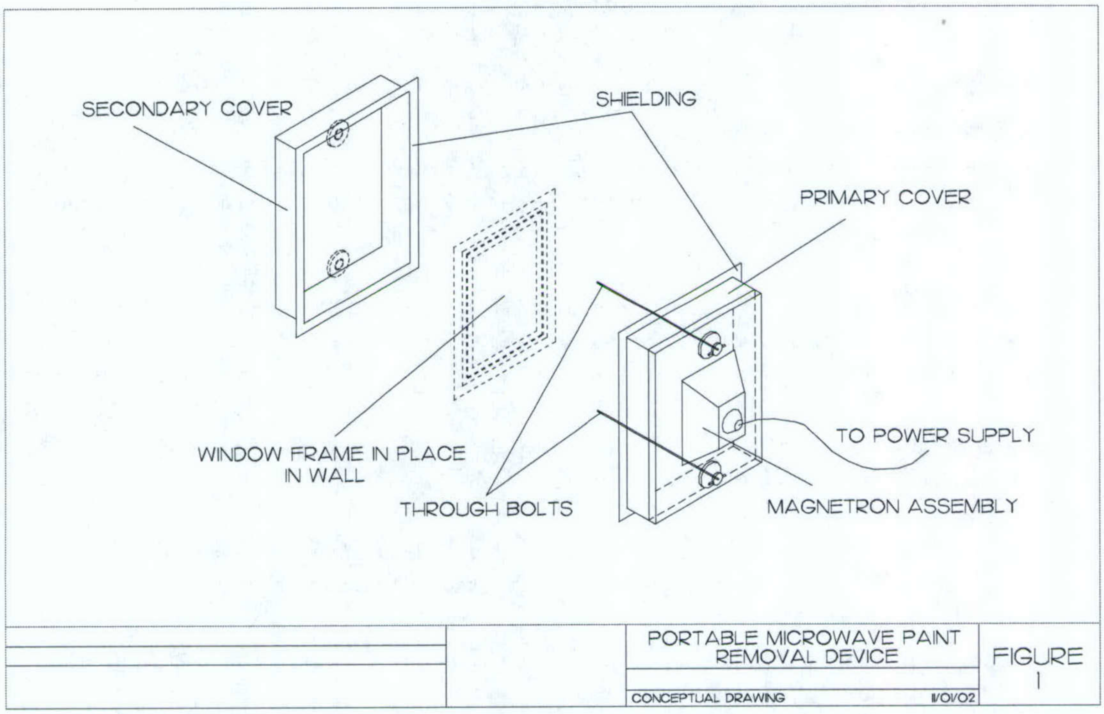


Figure 18. Design for *in situ* microwave paint stripping device for windows and doors.

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Appendix A: AeroLead™ Airborne Lead Dust Monitor

Description

Under the Small Business Innovative Research (SBIR) program, the U.S. Navy funded the development of an airborne sampling and analysis monitor for use at small arms ranges and lead paint abatement sites. Environmental Life Support (ELS) Technology, Inc., developed the AeroLead™ Airborne Lead Analyzer (Figure A-1), based upon anodic stripping voltammetry (ASV). The selection criteria included analytical sensitivity, potential for automated operation, instrument cost, analysis time, and simplicity of operation.

Figure A-1. AeroLead system for detection of lead in air.

This instrument represents a portable, automatic, low-cost method to analyze airborne lead and lead dust contamination onsite and in near real-time. It can provide near real-time, single-sample ambient air monitoring and personal breathing zone (PBZ) analyses during lead-based paint (LBP) abatement projects, and near small arms ranges (especially indoor ranges), and is intended to result in a greater level of worker safety by providing portable, automated, onsite quantification of airborne lead concentrations to which the workers may be exposed. The working range of the AeroLead™ is 3-300 µg of lead. Data can be downloaded to a personal computer (PC) through an RS-232C port, and software is available to allow the user to import the data directly into MS Excel® in real-time, where it can be easily graphed.

This device sucks in air from within the PBZ, and traps any particulates on the filter. At the end of each 30-minute measuring period, the particulates, in this case, lead dust, are solutionized, the lead is plated out by electrolysis, and its concentration is determined by ASV.

This device was previously tested by the Navy at the Naval Amphibious Base, Little Creek, VA, in January 2000 U.S. Department of Defense 2002)*. The Navy results showed that there was a high degree of variability in performance between units, with precision varying between 15 and 87 percent at three standard lead concentrations tested. Also, accuracy ranged from 29 to 75 percent, with the Aerolead device overpredicting the lead concentrations. It is believed that this variability is due to the electrode designed, which has since been modified by the vendor.

Lead Dust Monitoring During Microwave Removal Technology Demonstration

Two different measurement systems were used for monitoring the lead concentration in air when the actual process of microwave-assisted stripping of LBP was being carried out: the conventional EPA Method 7300 and the AeroLead.™ Airborne Lead Analyzer.

For EPA Method 7300, the operator wore a lead in air detection system on the collar to measure the lead being breathed National Institute for Occupational Safety and Health [NIOSH] 1994). A portable air pump sucked air through a filter worn near the operator's face. This measurement was carried out by Hart Crowser, Inc., Seattle, WA. The filter was analyzed at Hart Crowser's laboratory, and the result indicated that less than 35 micrograms/m^3 of lead was detected in air. This measurement is also consistent with the Hart-Crowser's detectable limit for lead samples

* References cited in this appendix are listed in the Reference section at the end of the main text.

obtained and analyzed in this way. The permissible exposure limit (PEL) for lead dust in air is 50 micrograms/m^3.

During the microwave-assisted paint removal technology demonstration, the AeroLead airborne lead monitor indicated an 8-hr time-weighted average of 5.18 micrograms/m^3. These results were determined from five runs of the AeroLead, which were all done onsite and were available within 7 minutes after the sampling periods of 15 to 30 minutes.

These results are well within the PEL of 50 micrograms/m^3. Thus, the AeroLead technique appears to be a much more sensitive method than the conventional EPA Method 7300. On the basis of these results and under the Environmental Security Technology Certification Program (ESTCP) testing, it is estimated that sampling costs were reduced from $25 to less than $3 per sample, and airborne lead analysis time was reduced from 3 days to about 7 minutes. Variability, accuracy, and precision are considered problematic, however, and these issues are being addressed by the contractor.

Appendix B: Experience from European Lead-Based Paint Stripping Initiatives

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Introduction

This report is an attempt to analyze the commercialization potential of various processes for the removal of lead-based paint from windows and doors.

The report will be based on the knowledge of European initiatives and especially on Danish initiatives.

The efficacy of various paint removal processes will be considered with special focus on the microwave-assisted techniques, considering both the "heating" technique and the "pyrolysis" technique.

We have made use of the Internet to find organizations and/or companies who offer services for window restoration and have searched the following countries: Sweden, Norway, Denmark, the United Kingdom and Ireland, Germany, Austria, and Switzerland.

The remaining European countries have been searched using search words in English and German but, due to lack of language knowledge, not in the respective native language.

The following search words were used, both individually and in combinations: microwaves, infrared, GHEM-base®, windows, restoration, renovation.

The following search engines have been used for searching the Internet: www.yahoo.com and www.google.com.

During our research we have also come across a report from 1998 from The Danish Ministry for Buildings in which the various paint-stripping methods (including microwave paint stripping) have been compared. As this is a very thorough analysis, we will make reference to part of it in this report where relevant.

Search Results

Sweden

Four results came up:

- www.gisip.se
- www.bygsam.nu
- www.fönsterhantverkarna.se
- www.kupolen-tingsryd.com

Comments:

1. Gisip is a manufacturer of microwave ovens.
2. Bygsam is a company using microwaves plain heating to perform paint stripping. Paint stripping is a side activity. The company's main activity is a do-it-yourself and home improvement market.
3. Fönsterhantverkarna is an organization/company dedicated to restoration of windows. The company/organization also sells a special "putty lamp" to soften hard putty so that a pane can be taken out of the frame before restoration.
4. Kupolen-tingsryd is the homepage for the company selling license to the GHEM-base method according to a Swedish patent which uses microwaves plain heating as a stripping method.

Norway

No results came up.

Denmark

Four results came up:

- www.larsen-facaderenovering.dk
- www.wood-tech.dk
- www.mts-entrepriser.dk
- www.raadvad.dk

Comments:

1. Larsen Facaderenovering was originally established in 1994 under the name of Nordahl & Axelsen A/S. The company started production in 1995 with one oven (make: IMITEC). In 1996 a small mobile oven for on-site stripping was bought. Today the company has a total of four ovens (three for fixed installation and one mobile). The company went bankrupt twice (in 1996 and 1999). In 2000 the company was bought by Mr. Bent Larsen and has today apparently changed its name to Larsen Facadeafrensning (Larsen Facade Cleaning) and has increased its field of activity.
2. WoodTech ApS was established in 2001 and started production in 2002. The company has one microwave oven (make: TORA). In the meantime the company has somehow joined forces with another company being active within the field of facade cleaning.
3. MTS Entrepriser A/S is a larger company established 1980. The company acts as a turnkey contractor on all aspects of maintenance of buildings. The company has two infrared ovens both bought in 2000.

For none of the companies has it been possible to gather information as to their number of employees or turnover, and only to a very limited degree has it been possible to get information about prices.

4. Raadvad is a consultative center concerned with knowledge and information regarding the conservation and restoration of the architectural heritage, traditional craft skills, and traditional building materials. The center collaborates with institutions and professionals in Denmark, the rest of Scandinavia, and Europe. The center has a good homepage, partly in English.

UK and Ireland

Only a single result came up from a company that sells the putty lamp as mentioned under Fönster Hantverkarna in Sweden.

Germany

Several results came up, but none of the companies were active within the field of paint stripping. All companies offered their service within the fields of (1) making copies of old windows, (2) exchanging old windows to new plastic windows, and (3) covering the timber parts of old windows with either aluminum or plastic.

Switzerland

No results came up.

Austria

No results came up.

Out of Search

www.restorationworksinc.com. Restoration Works, Inc., is an Illinois-based company. They claim that most likely they are the only company in the United States dedicated to window restoration. Their home page does not inform how they do the stripping, but otherwise the home page is very good and informative.

Danish Initiatives

As appears from the internet research, Denmark is most likely a pioneer in window restoration. In Denmark, windows have traditionally been painted with lead based paint until this type of paint was abandoned in the early 1950s.

Before being repainted, windows have thus been stripped by traditional stripping methods, i.e., chemical stripping, gas flame stripping, hot air jet stream stripping, and sanding. In a semi-industrial way, only the latter two methods have been used. During recent years new stripping methods been developed.

The use of microwaves for paint stripping was introduced in Denmark in 1994 when the company Nordahl & Axelsen A/S got a license agreement for a Swedish patent (SE470255 = EP0629157). According to this patent windows to be stripped are heated in a large microwave oven and subsequently the softened paint is scraped off. This process equals the process known from traditional household microwave ovens where the microwaves couple with water. The process thus requires that the wood contains a certain amount of humidity (approximately 20% according to SE patent 470255).

In 2002 a newly established company (WoodTech ApS) started production according to a new method developed and patented by U.S. Army Construction Engineering Research Laboratory (U.S. patent 5268548, Kumar 1993). According to this method, slurry of graphite is applied to the subject before it is inserted into the oven and exposed to the microwaves. A coat of stabilizer may be applied prior to the coat of graphite slurry, but such a stabilizer is not used in Denmark. When exposed to microwaves, the graphite will start to glow whereby the coat of paint is pyrolized.

Also in 2002 a company, MTS Entrepriser A/S, started with semi-industrial stripping of windows. This method, however, is based upon long-wave infrared radiation. It is assumed that this process basically is identical to the process according to the Swedish patent in so far that the humidity in the wood is heated.

Thus, during the past 3 years, three "specialized" companies have started production within semi-industrial stripping and restoration of windows in Denmark. All three companies are situated in or around Copenhagen.

We are not aware of companies outside Copenhagen who make use of one of the three methods mentioned.

The population of Copenhagen comprises 600,000 households against 2,500,000 for Denmark as a whole. On an average 40 percent of the Danes live in flats. However, this percentage is expected to be higher in and around Copenhagen.

Window Renovation versus Replacement

According to The Guild of Danish Glaziers, between 500,000 and 600,000 windows are taken to the incineration plant every year, and the Danes spend about $460 million every year on replacement of windows.

According to an investigation made by the guild, only 1 out of 10 windows made before 1960 are ripe for replacement. The remaining 9 would last for another 100 - 200 years if they were properly renovated and maintained.

According to the guild the main problem with windows is that quite often for aesthetic reasons the windows are either painted with the wrong paint or they are over painted. In both cases moisture penetrates the wood but cannot get out again, painted. In both cases moisture penetrates the wood but cannot get out again, with dry rot being the result.

When the question of renovation versus replacement of windows in a building is considered, there may of course be regulations to observe stipulating the appearance of the windows so as not to change the architectural look of the building in question. Such a regulation, however, is only part of the set of problems to be considered.

It is a general attitude that by replacing a window with a new and modern one, one will get a "better" window, but this is not necessarily always so. Quite often the timber quality of the older windows is far better than what can be obtained today at an affordable price. The lifetime for a "modern" window is stated to be 20-30 years (with an average of 15-20 years). To this should be added that older windows often have richness in details, which cannot be reproduced today.

Another aspect is the factor of time. Most owners would like to have a very strict timetable. With scaffolding and preliminary windows people get insecure.

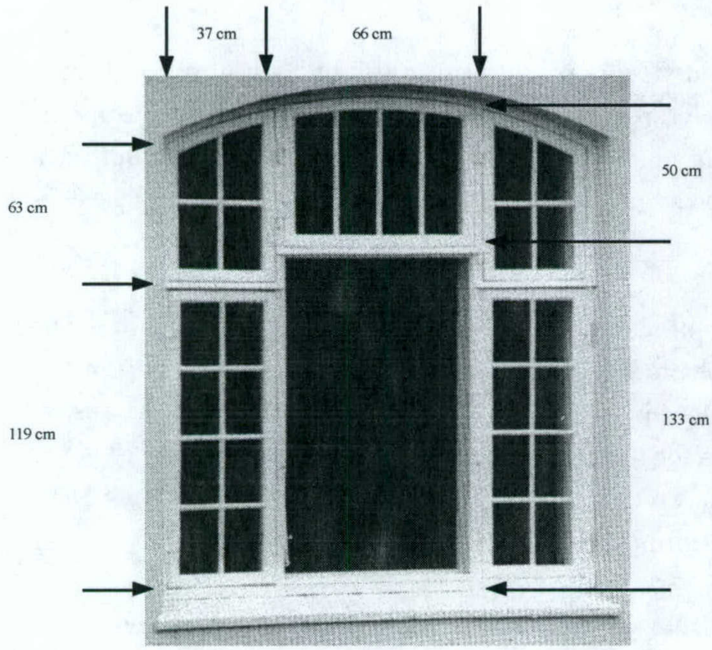
A third aspect is the price. Normally it is fairly simple to calculate the price for replacement of windows. In Denmark the replacement of a window of average size will amount to $ 750 – 1000. If it comes to renovation, the calculation is more complex and requires experience as to the extent of repairs. According to information obtained from the Danish market, renovation of a standard window (including removing, refitting, and average repair) will be at the same amount.

Comparison of Processes

As mentioned in the introduction, The Danish Ministry for Buildings in 1998 made a report in which the various stripping methods were compared. Except when stripping with microwaves, where the putty is softened so that the glass can be taken out, then all methods involve the same procedures. Therefore, by testing the various methods upon the same type of window, it was possible to compare the various methods as to:

- Sound level.
- Exposure to dust.
- Exposure to lead.
- Power consumption.
- Total working time.

The various methods have been tested upon a window as shown in the table below.



Key values of the compared methods

	Sound level	Exposure to dust	Exposure to lead	Heating time (total for both sides)	Stripping time (total for both sides)	Power consumption for stripping one frame	Total working time for one frame (both sides)
Hot air jet stream	81 dB (A)	1.59 mg	0.29 mg	75 minutes	75 minutes	3 kWh	215 minutes
Sanding	81 dB (A)	24.9 mg	3.7 mg	N/A	175 minutes	2.3 kWh	255 minutes
Microwaves,plain heating	81 dB (A)	0.96 mg	0.065 mg	35 minutes	20 minutes	5.5 kWh	225 minutes
Infrared heating	*81 dB (A)*	*0.96 mg*	*0.065 mg*	*35 minutes*	*20 minutes*	*13 kWh*	*200 minutes*
Microwaves, pyrolysis method	*81 dB (A)*	*0.96 mg*	*0.065 mg*	*10 minutes*	*20 minutes*	*3 kWh*	*200 minutes*

All values are measured except those in italic type, which are either estimated or obtained through other sources. All values are "per frame."

"Total working time" includes all processes from taking out the window until it is fitted again. "Power consumption" includes power for all machinery used for the renovation process.

The upper limit in Denmark for "exposure to lead" is 0.05 mg.

The upper limit in Denmark for "exposure to dust" is 10 mg for mineral dust and 5 mg for organic dust.

The information about infrared heating and microwaves, pyrolysis method, was not included in the report made by the ministry but has been added by us for comparison.

As infrared heating by its nature is very similar to microwave heating, it is assumed that the values in regard to the exposure to dust and lead will be identical. According to information obtained, heating time will be about the same as for microwaves; but as the panes are not taken out, total renovation time will be reduced.

OBS: Using infrared heating the panes will also be heated and will, to a large extent, break. Infrared heating should therefore not be used for ancient or special panes. It is, however, possible to buy a special "putty lamp" to soften the putty and thus take out the pane before the frame is being treated.

It is assumed that the values in regard to the exposure to dust and lead for "microwaves, pyrolysis method" will be identical to microwaves, plain heating.

How far a stabilizer like Lead-X or PreTox 2000® will reduce the exposure to lead during stripping will have to be tested.

If such a stabilizer is used, then the time for the application will have to be added to "total time."

This also applies to microwaves plain heating and infrared heating.

Seen from an occupational health point of view, only the microwave and the infrared method seem to meet a satisfactory standard, so that they can be used in a semi-industrial way.

Microwave Versus Infrared Stripping

From the table above we have seen that from an occupational health point of view, only the microwave and the infrared stripping methods are relevant for semi-industrial purpose. But how do these processes differ and are they equally efficient?

Infrared Stripping

Like microwave stripping, infrared stripping is carried out by inserting the window or the door into an oven. Instead of being equipped with magnetrons, the oven is equipped with special ceramics radiating long-wave infrared radiation.

To secure the efficacy of such an oven, the rating should be at least 8 kW per square meter cavity, preferably 15 kW. It is recommended that the ceramics should be switched independent of each other. Such an oven is cheaper to buy than a microwave oven, but more costly to run.

Although being long wave, these waves do not penetrate far into the wood, but due to the relatively long heating time (about 12 minutes per side) the heat will spread in the timber from the outside and inward. When both sides of a window frame have been heated and stripped, the center of a frame will have reached a temperature of about 100 °C or more, which is also high enough to kill dry rot.

As we have mentioned before, infrared heating is not suited for frames with ancient or rare panes, as panes, due to the heat, will most likely break unless they have been taken out before the frame goes into the oven. This can be done by using the so-called putty lamp, but such a procedure will of course increase the stripping time considerably.

Another disadvantage of the infrared stripping method is that as soon as the paint has cooled, it gets hard as glass and cannot be softened again by a second treatment. The result is extra time for the after treatment, i.e., sanding.

Infrared stripping has, however, one advantage: it is fairly easy and safe (although slow) to operate as a handheld unit. It is also possible to make large units for scanning (i.e., stripping) whole walls.

It is not known to what extent a stabilizer will have any effect on infrared stripped lead-based paint.

Microwave Stripping, Plain Heating

Paint stripping using the microwave plain heating method can be performed only on material that contains moisture. The reason is that the microwaves couple with the water in the material and heat it. The heated water penetrates from the inside and out, thus heating and softening the paint.

Because object is always heated inside out, it is therefore a more complex matter to design such an oven as, to a large extent, the rating of the oven will depend upon the volume of the object it has to handle. In general, however, a microwave oven for plain heating can be made at half the rating of an infrared oven and still do the same job.

As the object is always heated inside out, it will have a higher temperature in the core than on the outside. Typical temperatures for a window frame will be an outside temperature of approximately 100 °C and a core temperature of about 120 °C – 130 °C. Such a core temperature will also kill dry rot efficiently.

It is important that the stripping can be completed as long as the wood is hot and the paint is soft. Especially corners tend to be problem areas as they cool down fairly quickly and often have thicker layers of paint.

A subsequent treatment will not soften the paint again to any useful degree, most likely because the moisture has already left the object so that there is no moisture left to soften the paint if/when the frame is heated a second time.

As previously mentioned, microwaves will not heat panes. When microwaves are used for paint stripping, there is no need to take out the panes before the object goes into the oven. When the window comes out again, the putty is soft and can easily be removed.

It is not known to what extent a stabilizer will have any effect on stripped lead-based paint using the microwave plain heating method.

Microwave Stripping, Pyrolysis Method

Paint stripping using the microwave pyrolysis method tends to be very much like the plain heating method as the pyrolysis method is carried out in a similar oven. The rating of such an oven can, however, be reduced by up to 50 percent if it is used solely to perform the pyrolysis method.

The difference from the plain heating method is that when the pyrolysis method is performed, the object has to be "painted" with a susceptor (a slurry of graphite) before being inserted into the oven. Tests have been carried by the Danish company WoodTech where such a slurry was mixed as described in U.S. patent 5268548 (Kumar 1993) (i.e., 28 wt percent graphite powder mixed with 43.2 wt percent latex paint and 28.8 wt percent water). When exposed to microwave radiation, this slurry will reach a temperature of about 1200 °C within a few minutes. When the microwaves are switched off, the temperature instantly decreases to about the obtained core temperature of approximately 65 °C. In U.S. patent 5268548 it is claimed that this susceptor can be used in combination with a stabilizer to prevent the leaching of lead from the removed paint. Such a combination has not been tested.

The pyrolysis method has proved to have several advantages over the plain heating method:

1. The oven can be made at a smaller kW rating, although this is not recommended as it will prevent one from using the plain heating method if necessary.
2. The heating time is reduced by about 50 percent.
3. Although the heating time is reduced, the softened paint scrapes off extremely easily, and, contrary to the plain heating method, the pyrolysis method may be repeated if necessary,
4. Corners tend to be easier to scrape off using the pyrolysis method,
5. The process is carried out at a generally lower core temperature.
6. This, however, can also be seen as a disadvantage especially if the wood contains a lot of humidity. Extra heating time may then be required.

Although the slurry starts to glow when exposed to microwaves, no pane has broken yet although the edges of the panes, at some places, have also been slightly painted with the slurry. Also the putty gets just as soft with the pyrolysis method as with the plain heating method, in spite of the reduced heating time.

The only disadvantages found are as follows:

1. The extra time and cost to prepare the susceptor slurry.
2. The extra time and cost to apply the susceptor slurry.
3. The waiting time for the slurry to dry, but this point is merely a matter of planning.

However, if an additional stabilizer is used, it should be possible to charge a slightly higher price for the stripping due to the environmentally safe way it is done.

It may be worthwhile to consider if the pyrolysis method could be used for other purposes e.g., a handheld unit for removing graffiti or an extra large unit running on trails for stripping whole facades.

Conclusion

The U.S. Army Engineer Research and Development Center has developed a special "microwave-assisted paint stripping" method. The method has been patented under U.S. patent No. 5268548. A Danish company has shown interest in the method and is now using it for restoration of windows.

It has been the aim of this report to find out to what extent, if any, this method will fit into existing methods for window restoration.

Through the Internet we have scanned the European market for window restoration to try to find out how many companies are active within this field and possibly which methods they use. Only four companies were found who make real restoration: three Danish companies, one Swedish company and – out of search – one American company.

All European companies carry out their activity on a semi-industrial basis and use either microwaves or infrared for heating the windows before stripping. As to the U.S. company, no indication is given in their homepage concerning their choice of method.

All other European companies who claim to be active in window restoration either make copies of windows, change wooden windows to plastic or aluminum windows, or cover existing wooden parts of a window with either plastic or aluminum.

This report is therefore based upon Danish experience.

In Denmark, during the last decade there has been an increased interest in not only saving energy, but also in preserving the architectural heritage. As a combination of these two interests a small market has developed for the restoration of windows, at the beginning initiated by the public hand and with only a single company being active in this field. Today, however, the market has grown to three companies offering restoration service, and the interest for preserving and restoring old and original windows has spread also to private owners of buildings of special architectural or historic interest.

The reason for this increased interest may partly be that restoration has reached a level where a properly restored window will last for another 100 years, partly because the cost for such a restoration has come down to a level where it is almost comparable to the cost of a new and modern window, which, however, will only last for 20 – 25 years.

As all three companies are active within the geographical area of Copenhagen, and as all three companies today carry out their restoration activity together with other activities, this could indicate that a certain customer base is required to run this activity profitably, at any rate on a contractor basis.

When it comes to the stripping processes, only three are acceptable from an occupational health point of view: infrared stripping, microwaves plain heating, and the microwaves pyrolysis method.

Infrared heating will do the job but has the disadvantage that it is rather power consuming compared to the microwave processes. Another disadvantage is that the panes will normally break when exposed to infrared heating. To take the pane out before the frame goes into the oven will mean extra cost. Yet another disadvantage of the infrared heating is that only one treatment can take place. The softened paint must be scraped off in one operation. If it cools down it gets hard as glass.

Microwave plain heating has the advantage that it is not necessary to take out the panes before the frames go into the oven. Microwaves will not heat the glass, and after treatment the old putty is soft and can easily be cut off. A microwave oven for plain heating can be made at half the rating of an infrared oven and still do the same job. A disadvantage is that paint softened through microwave plain heating also must be scraped off in one operation. A second treatment will not soften the paint again.

The microwave pyrolysis method is very similar to the plain heating method but has some additional advantages. It is even less power consuming than the plain heating method, the processing time is shorter, and the procedure may be repeated a second time if necessary. As an additional advantage, it is claimed that the graphite slurry required may be combined with a stabilizer, which will prevent lead from the paint leaching into the environment. How far such a stabilizer may be used in the other two processes is not known. The only disadvantage found in the microwave pyrolysis method is the extra time and cost for mixing and applying the graphite slurry, but this extra cost may be marginal if calculated per window, and will most certainly be balanced through the reduced power consumption.

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14. ABSTRACT

The microwave-assisted paint removal process is a viable alternative to the currently used technologies for lead-based paint (LBP) removal, such as abrasive blasting and chemical stripping. Two design approaches for the microwave paint removal systems were evaluated for removal of LBP. Graphite-based susceptor materials, applied over the painted surface, were used successfully in absorbing the microwave energy and heating the paint. The heat softened the paint, which was easily scraped from the substrate. The microwave paint removal process was optimized in the laboratory and field demonstrated for a wooden window sill and trough at Fort Lewis. The lead levels on the relatively flat substrates and complex shaped substrates were dramatically reduced on the areas stripped. Chemical stabilizers applied over the LBP prior to application of the susceptor rendered the waste nonhazardous by the current Resource Conservation and Recovery Act (RCRA) Toxicity Characteristic Leaching Procedure (TCLP) criteria. The microwave-assisted removal process is safe and effective in removing paint without burning, discoloring, or otherwise damaging the substrate.

15. SUBJECT TERMS
lead-based paint (LBP), microwave, hazardous waste, paint removal, environmental compliance, wooden structures, Fort Lewis, WA

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